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Smart Structures and Materials '93

Damage Detection and Mitigation of Composite Structures Using Smart Materials

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1. Abstract

This paper reports the results of an ongoing experimental program for damage assessment and mitigation of composite structures using smart materials. One consequence of all damage to a composite structure is a change in its stiffness. This change in stiffness is measured by modal analysis which can be carried out using piezoelectric films as both sensor and actuator on the structure member. It is shown that the presence of damage can be detected by the change in natural frequencies and the location of the damage can be detected from the ratio of changes in frequencies between two successive modes. Experiments are now being carried out using healthy and damaged composite beams of rectangular cross section with piezoceramic sensors and actuators. In this paper experimental results of damage detection will be described in detail.

2. Introduction

This research consists of an experimental program for damage detection and mitigation of composite structures using smart materials. All load-carrying members of structures continuously accumulate damage in their service environment. In order to ensure safe operating conditions it is necessary to monitor the damage continuously and to take temporary corrective actions by redistributing the load to minimize the effects of such damage until the structure can be repaired.

The consequences of all damages in composite structures are changes in stiffness, strength, and fatigue properties. Measurement of strength or fatigue properties during the damage development is not feasible because both of them require destructive testing. However stiffness can be measured frequently during damage development because it directly effects the dynamic response of the structure. The most widely used method for damage assessment is to identify the occurrence, location, and extent of the damage from measured structural dynamic characteristics. Therefore, the relationship between the physical parameters, such as mass and stiffness, and the dynamic characteristics, such as eigenvalues and eigenvectors, must be determined by modal analysis.

In the proposed method the modal analysis will be carried out using piezoelectric films as both sensor and actuator on the structure member. Using a piezoelectric actuator it is possible to excite the member at different sinusoidal frequencies and with a piezoelectric sensor the response of the member can be measured and the dynamic parameters of the structure can be evaluated. The advantage of using smart materials for the system identification is that the condition of the structure can be continuously monitored and, by using an onboard microprocessor, the sensor output can be continuously evaluated.

Once the presence of a defect has been detected the next step is to locate the damage and determine the type of damage. At this stage no analytical model is available to locate the position and the type of damage from system identification data. In this proposed research a finite element model of the damaged structure will be used to calculate the theoretical change in frequencies due to different damage locations which will then be compared with experimentally obtained change in frequency to locate the damage. An alternate method would be to train a neural network with dynamic responses that result from structures with a known location and type of defect. After sufficient training the network should be able to find the position and type of defect in a damaged structural member.

The last step of the process consists of mitigation of the damage. The smart structure will be embedded with piezoelectric patches to change the stiffness and damping of the structure so that the loading on the damaged structure can be redistributed to minimize the effect of such damage.

3. Type of damages

The most frequently occuring damages for composite materials are fiber fracture, matrix cracking and delaminations. *Fiber fracture* can degrade the strength and stiffness of composite structures significantly. As each fiber breaks, the redistribution of stress leads to additional stresses on neighboring fibers. Thus, there is an increased probability that fracture will occur in the immediately adjacent fibers. This increases as load increases and eventually sequential fiber fracture occurs. *Matrix cracking* is the cracking of the resin within a layer. Fibers perpendicular to the loading direction produce stress concentration in the matrix. Since the failure strain of the matrix is lower than that of the fiber, when subject to a load, the difference in failure strain causes the matrix to crack. The third kind of damage, *delamination*, appears as debonding of adjoining plies in laminated composites[13]. It may result from impact, eccentric loading, discontinuities or during manufacturing. The presence of delamination prevents proper load distribution between plies, and the composite is reduced to a number of independent longitudinal plies acting in parallel to support the load. The weakest of these plies fails and may trigger the failure of remaining plies.

Of these various damages, delamination will be considered thoroughly in the present work.

4. Background

4.1 Damage Detection

Adams et al.[1] first found that a state of damage with fiber reinforced plastics could be detected by a reduction of stiffness and increase in damping. A change in stiffness change the natural frequencies of a vibrating system whether the damage is localized or distributed. So, the measurement of natural frequencies of a structure at two or more stages of its life can locate damage in a structure. In a later paper Adams et al.[2] presented a method for determining damage location by receptance analysis. It was shown that vibration measurements made at a single station in a structure can be used in conjunction with a suitable theoretical model to indicate both the location and the magnitude of a defect. Cawley et al.[4] used finite element analysis for finding the damage location. They have shown that the ratio of the frequency changes in two successive modes is a function of the damage location. The basis of the method is to consider damage as a local decrease in stiffness of the structure.

Tracy J.J. and Pardoen G.C.[14] presented the results of a study on the effect of prescribed delamination on the natural frequencies of laminated beam specimens. They used experimental modal analysis to measure the effect of delamination length on the first four frequencies of simply supported test specimens. The presence of delamination degraded the even numbered vibration modes much more rapidly than the odd numbered modes for a delamination centered at the specimen midspan.

4.2 Modelling of Damage

Mujumdar et al.[12] presented an analytical model of a delaminated beam as four separate component segments each analyzed as an Euler beam. Hu et al.[11] analyzed the growth of dynamic delamination using the finite element method. They used beam elements with nodes offset either to the top or bottom side. The delaminated beam is modeled as two beams above and below the plane of delamination and spring elements and rigid elements are used to connect the beams above and below the plane of delamination. Tracy et al.[14] presented an analytical model that assumed that the delamination divides the beam into four regions and extends over the entire width. Although this model is good for determining the natural frequencies of composite lamina, it is not suitable for use in simulation of structural control.

4.3 Use of Piezoelectric materials

Crawley et al.[4] first presented work on analytic and experimental development of piezoelectric actuators as elements of intelligent structures. Static and dynamic analytic models are derived for segmented piezoelectric actuators that are either bonded to an elastic substructure or embedded in a laminated composite. These models provide the ability to predict the response of a structural member to a command voltage applied to the piezoelectric and give guidance to optimal location for actuator placement. Baz and Poh[3] presented a Modified Independent Modal Space Control method to select the optimal location, control gains and excitation voltage of the piezoelectric actuators. Hanagud, et al.[8] presented the experimental and analytical studies to compare the performances of polyvinilidene fluoride films and piezoelectric transducers for modal analysis. In a later paper Hanagud et al.[9] presented a finite element model for an active beam with many distributed piezoceramic sensors and actuators coupled by an electrical conditioning system.

5. Experimental Results

In order to carry out experiments Carbon Fiber / Bismalimide Resin laminates with various lengths of known delaminations were made. AMOCO T-650142-121C/MR-56-2 unidirectional tape was used to fabricate 16 ply, 2.4mm laminate with a $[90_2,30_2,45_2,90_2,60_2,30_2,90_2,45_2]_T$ stacking sequence. Various length delaminations were manufactured into the part by placing fluorinated ethylene propylene (FEP) tape at the midplane of the laminate between plies 4 and 5. The tape prevents bonding between the two plies adjacent to the FEP regions. Individual test specimens 287 mm long by 25.4 mm wide were machined out from the laminate using a water jet cutter to prevent further damage. The test specimens were cut in such a way that the tape provided a full width delamination located midway along the length of each sample.

The experimental setup for modal analysis of the clamped-free composite beams are shown in Fig.1. The free ends of the beams are hit by a conventional impact hammer to excite a broad range of frequencies and the response of the beam is sensed by an accelerometer. Both the impact and response signals were analyzed in an ONO SOKKI dual channel FFT analyzer. The tip of the impact hammer is chosen such that impact force is constant (Fig.2) up to a frequency which is considerably higher than the first five modes the accelerometer was able to sense. The plots of the responses obtained are shown in Fig.3-6. The frequencies for each mode are tabulated in table 1. It can be seen that for all the modes, there is a decrease in natural frequencies, unlike explained by Tracy et al.[14] where there was more degradation for even numbered modes than odd numbered modes. This may be due to the unsymmetric nature of the laminates where a high degree of bending/extensional coupling is present.

6. Work in Progress

Efforts are now underway to compute theoretically the ratio of changes in natural frequencies between successive modes which would then be equated with the experimentally obtained ratio to find the damage location. For that the first step is to come up with a model of the damaged beam which is detailed enough to give the theoretical natural frequencies but also is versatile enough so that the models of the piezoceramic sensors and actuators can be augmented to it to perform the theoretical modal analysis and simulation of damage mitigation. All the models described in the references are under study for this purpose. Once a suitable model is obtained, the next step would be to carry out the modal analysis using piezoceramic sensors and actuators (Fig.7) and optimal redistribution of strain in the structure using suitable actuation of piezoceramic actuators.

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8. References

1. Adams, R.D., Walton,D., Flitcroft, J.E., Short,D., "Vibration Testing as a nondestructive test tool for composite materials', Composite Reliability ASTM STP 580, American Society for Testing and Materials, 1975, 159-175.

2. Adams,R.D., Cawley, P., Pye, C.J., and Stone, B.J., "A Vibration Technique for Non-Destructively Assessing the Integrity of Structures", Journal of Mechanical Engineering Science, Vol.20, No.2, 1978, pp.93-100.

3. Baz, A. and Poh, S., "Performance of an Active Control System with Piezoelectric Actuators", Journal of Sound and Vibration, Vol.126, No.2, 1988, pp.327-343.

4. Cawley, P. and Adams, R.D., "The Location of Defects in Structures from Measurements of Natural Frequencies", Journal of Strain Analysis, Vol.14, No.2, 1979, pp.49-57.

5. Cawley, P., and Adams, R.D., "A Vibration Technique for Non-Destructive Testing of Fibre Composite Structures", Journal of Composite Materials, Vol.13, April 1979, pp.161-175.

6. Crawley, E.F., and Luis, J.D., "Use of Piezoelectric Actuators as Elements of Intelligent Structures", AIAA Journal, Vol.25, No.10, October 1987, pp. 1373-1385.

7. Chen, Jay-Chung and Garba, J.A., "On-Orbit Damage Assessment for Large Space Structures", AIAA Journal, Vol.26, No.9, September 1988, pp.1119-1126.

8. Hanagud, S.V. , Savanur, S.G., Nagesh Babu, G.L., and Won, C.C., "Modal Analysis with PVDF Films and Piezoceramic Transducers", Proceedings of ASME Winter Annual Meeting, December, 1991.

9. Hanagud, S. , Obal, M.W., and Calise, A.J., "Optimal Vibration Control by the Use of Piezoceramic Sensors and Actuators", Journal of Guidance, Control and Dynamics, Vol.15, No.5, September-October 1992,pp.1199-1206.

10. Hajela, P. and Soeiro, F.J., "Structural Damage Detection Based on Static and Modal Analysis", AIAA Journal, Vol.28, No.6, pp.1110-1115.

11. Hu, S., Sankar, B.V., and Sun, C.T., "A Finite Element Study of Dynamic Delamination Growth in Composite Laminate', AIAA Paper No. 89-1301-CP. Collection of Technical Papers Presented at 30th SDM Conference,1989, pp. 1223-1233.

12. Mujumdar, P.M. and Suryanarayan, S., "Flexural Vibrations of Beams with Delaminations", Journal of Sound and Vibration, Vol.125, No.3, 1988, pp.441-461.

13. Teboub, Y. and Hajela, P., "A Neural Network Based Damage Analysis of Smart Composite Beams", Proceedings of 4th AIAA/USAF/NASA/OAI Symposium on Mutidisciplinary Analysis and Optimization, September 1992.

14. Tracy, J.J, and Pardoen, G.C., "Effect of Delamination on the Natural Frequencies of Composite Laminates", Journal of Composite Materials, Vol.23, December 1989, pp.1200-1215.

15. Tracy, J.J., Dimas, D.J., and Pardoen, G.C., "Advanced Composite Damage Detection Using Modal Analysis Techniques",

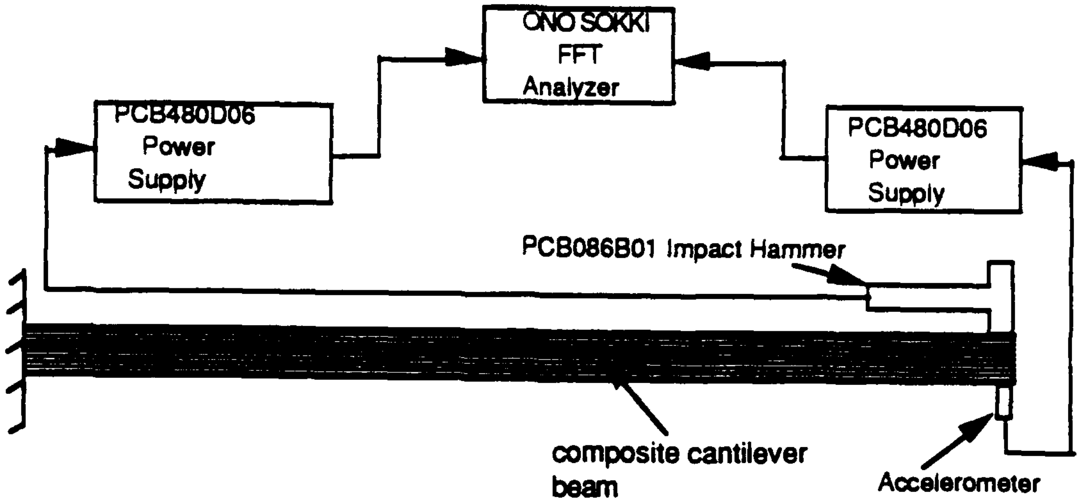

Fig.1: Impact Hammer modal analysis

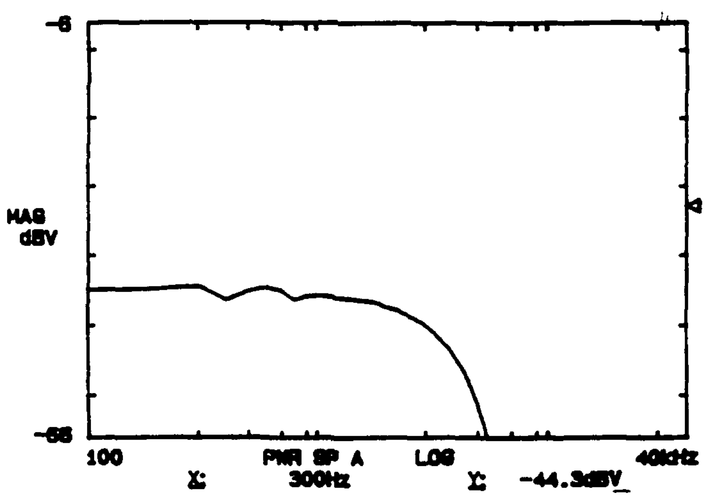

Fig.2: Frequency spectrum of hammer impact

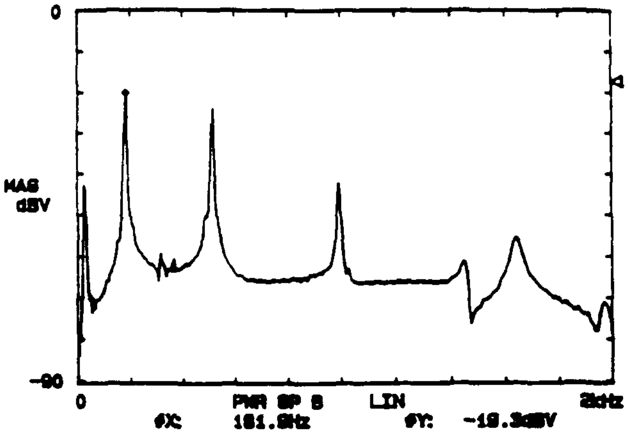

Fig.3: Frequency spectrum with no delamination

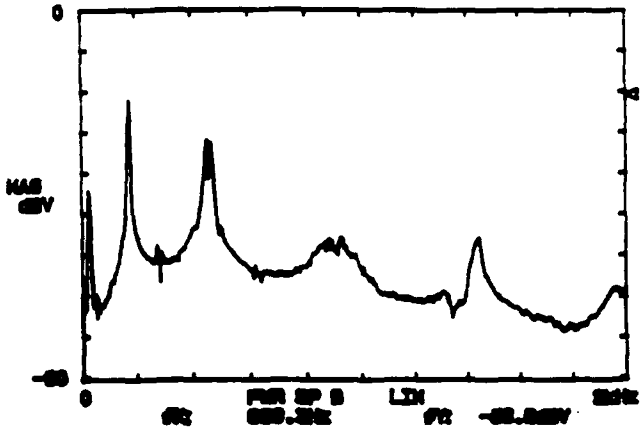

Fig.4: Frequency spectrum with 10% delamination

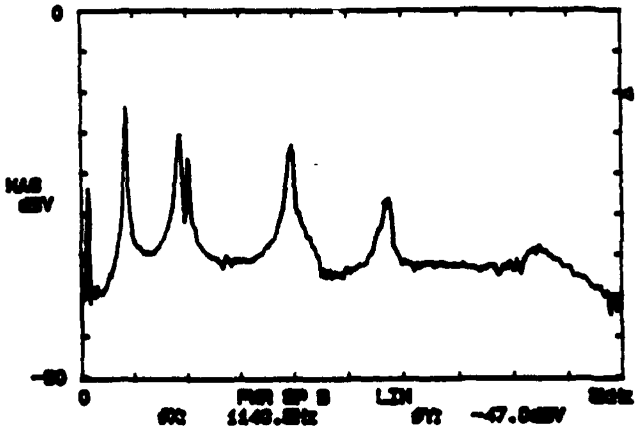

Fig.5: Frequency spectrum with 25% delamination

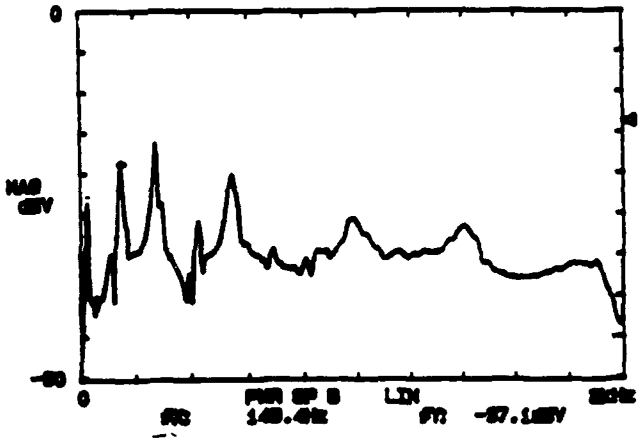

Fig.6: Frequency spectrum with 40% delamination

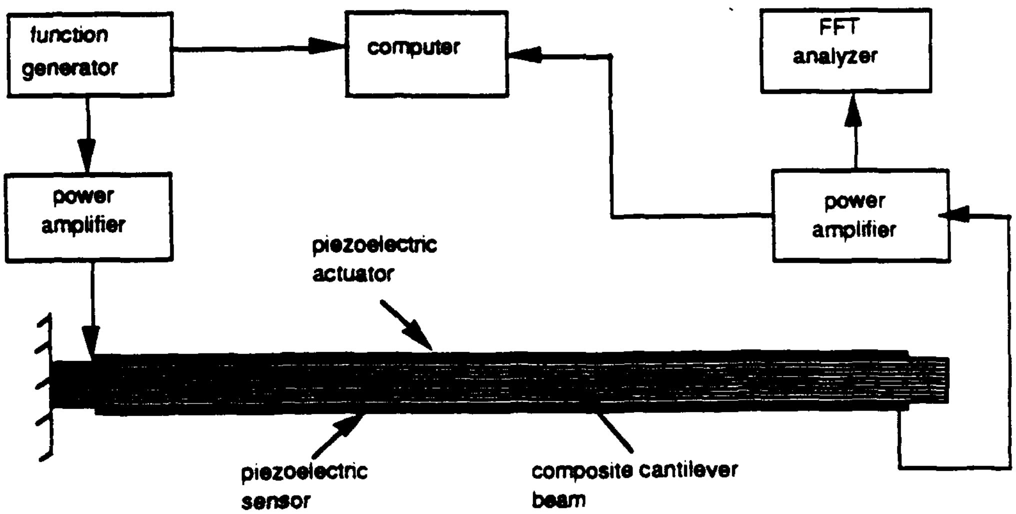

Fig.7: Modal analysis with Piezoceramic Materials

Table 1. Clamped-free composite beam modal analysis test results

	Natural Frequency (Hz)					
Sample ID	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Comments
1	27.7	181.9	515.3	995.2	1644	No delamination
2	26.4	175.3	453.7	920.0	1440	10% delamination
3	26.6	170.5	370.0	795.0	1149	25% delamination
4	24.0	146.0	275.0	545.0	980	40% delamination